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DELAYED NEUTRON CALCULATIONS USING ENDF/B-V DATA

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Data from 27 fission yield sets in ENDF/B-V are used with the emission probabilities (Pn) of 105 delayed neutron precursors to calculate fission and total equilibrium delayed neutron yields ($\bar{\nu}_d$). Results are compared with recent evaluations and selected measurements of $\bar{\nu}_d$. Least squares data adjustment methods are in progress to improve agreement; preliminary results indicate significant improvement when fission yields are adjusted.

The extensive fission-product yields and delayed neutron emission probabilities (Pn) have been incorporated in ENDF/B-V to permit calculation of $\bar{\nu}_d$ and its individual nuclide and group components. In addition, there are now sufficient measurements of the neutron spectra from individual precursors to permit aggregate spectral calculations. At the IAEA Fission-Product Nuclear Data Meeting in Petten in 1977,[1] it was noted that the future effort in improving delayed neutron data should emphasize improvement in the nuclear and fissionable data [illegible] maximum role of neutron energies, in light of the delayed neutron spectra. This report shows the current status of our calculations, but it is not the final word as there are still [illegible] exist in nuclide yields and the data for many [illegible] are available for ENDF/B-V evaluations.

Our studies of $\bar{\nu}_d$ have been in part in progress as part of the ENDF/B fission yield testing since [illegible]. Calculated $\bar{\nu}_d$ values are presented in the fission yield evaluation or report thereof, requiring [illegible] extensive Pn values, the calculated $\bar{\nu}_d$ values serve as an additional indication of the quality of fission product yield sets. [illegible] sufficiently accurate to justify the emphasis suggested at the 1977 Petten Meeting.

Table I lists Pn values for 105 precursors, the percent contribution to the $\bar{\nu}_d$ of ^{235}U thermal fission and other information. Based simply on energetics, all are probable delayed-neutron precursors; 67 have measured Pn values and 38 have Pn values we have estimated based on a simple phenomenological model. Since 1977, there have been 15 new measurements, identified in Table I, all being previously incorporated in preliminary ENDF/B-V files based on energetics. Use of the newly measured Pn values in place of the previous model estimates alters the calculated $\bar{\nu}_d$ for ^{235}U by only 0.01%. Model estimates of the remaining 38 unmeasured values are unlikely to significantly alter the calculated $\bar{\nu}_d$, particularly because these collectively contribute only 4% in these calculations. However, very large errors in some individual Pn estimates are likely. The estimated values can be identified in Table I by the lack of a tabulated uncertainty. Measured values in Table I incorporate values from the preliminary data at the March 1979 Consultants' Meeting in Vienna.[2] Data differing from that of Ref. 1 are also identified.

Table II lists the results of calculations and comparative results from evaluations and selected measurements. The T, F, and H following the fissionable nuclide refer, respectively, to Thermal, Fast, and High energy (7-14 MeV) fission. Because of the large number of $\bar{\nu}_d$ measurements, particularly for some (but not all) of the fissionable nuclides, only a selection of these can be listed in this table. A little recent or extensive review of measurements of $\bar{\nu}_d$ and an evaluation are those of Tuttle[3] and Keepin[4] whose preliminary evaluations are listed in Table II. The uncertainties listed for the calculations are based on fission-product yield uncertainties in ENDF/B-V and the Pn uncertainties in Table I. A 10% uncertainty was assigned to the estimated Pn values, but this is not a significant component of the listed $\bar{\nu}_d$ uncertainty. Except for ^{233}U thermal fission, the calculated uncertainties are probably somewhat small. The $\bar{\nu}_d$ calculations are sensitive to the yield distributions along each mass chain. This distribution is based on models using parameters derived largely from ^{235}U independent yields. Errors in the most probable charge or nuclear pairing effects could readily alter the $\bar{\nu}_d$ values, even if mass chain yields are exact. Thus, the yield uncertainties for some nuclides far from stability are likely too small. We suspect that the calculated $\bar{\nu}_d$ from ^{238}U fast fission for example, is small because of the large Z-pairing used in the yield evaluation.[3,5] Most (>90%) of the delayed neutrons are emitted from odd-Z precursors, and a relatively small error in the pairing could create a large error in $\bar{\nu}_d$. In any case, the yield uncertainties for very unstable nuclides probably do not adequately reflect the paucity of data available to predict model distribution parameters for most of the 270 yield sets used in this report.

Calculations of $\bar{\nu}_d$ require a mass imbalance of the yielded fission products of only ~0.01 units out of ~230, a stringent demand on the fission yields, and one that is not incorporated into the fission-product yield evaluation procedure. In view of this requirement, it is remarkable that only 5 of the 27 calculated values appear in significant error when compared with evaluations or measurements and their respective uncertainties.

TABLE I

DELAYED NEUTRON PRECURSORS

PRECURSOR ZZAAAM	HALF-LIFE (s)	Pn (%)	NO. OF SPEC MEAS	% of ν_d (235U)
Zn 300762	1.64	1.4	0	< 0.01
Ga 3[illegible]	3.06	[illegible]	1	< 0.01
Ga 3[illegible]	1.[illegible]	0.67 ±0.05[a]	1	< 0.01
Ga 310610	1.23	12.2 ±0.9[a]	1	0.05
Ga 310620	0.62	20.5 ±1.4[a]	0	0.06
Ge 320630	0.31	56.0	0	0.01
Ge 320640	1.4	[illegible]	0	< 0.01
Ge 320650	1.2	30.0	0	0.28
Ge 320660	0.234	22.0	0	0.05
Ge 320670	0.259	20.0	0	0.01
As 330740	1.4	[illegible]	0	0.02
As 330750	[illegible]	[illegible]	4	1.94
As 330760	[illegible]	[illegible]	0	[illegible]
As 330770	[illegible]	[illegible]	0	[illegible]
Se 340870	5.05	0.19 ±0.03[b]	0	0.08
Se 340880	1.52	0.5 ±0.3[b]	0	0.10
Se 340890	0.41	5.0 ±1.5	0	0.34
Se 340900	0.555	11.0	0	0.15
Se 340910	0.27	21.0 ±8.0	0	0.02
Br 350870	55.7	[illegible]	4	1.66
Br 350880	16.3	6.9 ±1.3[b]	1	7.90
Br 350890	[illegible]	[illegible]	2	10.36
Br 350900	[illegible]	[illegible]	3	8.16
Br 350910	[illegible]	[illegible]	1	1.01
Br 350920	[illegible]	[illegible]	0	0.45
Br 350930	[illegible]	[illegible]	0	0.07
Kr 360910	[illegible]	[illegible]	0	0.03
Kr 360920	[illegible]	[illegible]	0	0.56
Kr 360930	[illegible]	[illegible]	0	0.71
Kr 360940	[illegible]	9.0	0	0.04
Rb 370960	0.201	13.9 ±0.7[b]	1	1.62
Rb 370970	0.170	27.8 ±2.5[b]	2	1.23
Rb 370980	0.119	16.0 ±1.0[b]	1	0.02
Rb 370990	0.076	15.0 ±3.0[a]	0	< 0.01
Sr 380970	0.40	0.27 ±0.09[a]	0	0.31
Sr 380980	0.65	0.36 ±0.11[a]	0	0.14
Sr [illegible]	0.[illegible]	3.4 ±2.4	0	0.68
Sr [illegible]	1.0[illegible]	5.0	0	0.04
Y 390[illegible]	1.1[illegible]	0.06 ±0.02[b]	0	0.05
Y 3[illegible]	3.[illegible]	[illegible]	0	0.97
Y 39[illegible]	[illegible]	[illegible]	0	2.14
Y 390[illegible]	2.0	0.54	0	1.10
Y 390[illegible]	1.4	1.2 ±0.6	0	1.60
Y 391000	0.756	5.5	0	1.67
Zr 400[illegible]	3.[illegible]	0.11	0	< 0.01
Zr 401050	0.559	1.4	0	0.07

PRECURSOR ZZAAAM	HALF-LIFE (s)	Pn (%)	NO. OF SPEC MEAS	% of ν_d (235U)
Nb 411030	15.669	0.13	0	0.10
Nb 411040	1.0[illegible]	0.71	0	0.35
Nb 411050	1.8[illegible]	2.9	0	0.[illegible]
Mo 421060	0.93[illegible]	5.5	0	0.65
Mo 421070	1.033	0.53	0	< 0.01
Mo 421080	1.092	[illegible]	0	< 0.01
Tc 431090	56.00	[illegible]	0	< 0.01
Tc 431100	0.85	[illegible]	0	< 0.01
Ag 471110	[illegible]	[illegible]	0	< 0.01
Ag 471120	0.39	[illegible]	0	< 0.01
Cd 481280	0.[illegible]	[illegible]	0	< 0.01
In 491[illegible]	[illegible]	[illegible]	0	[illegible]
In 491[illegible]	[illegible]	[illegible]	1	[illegible]
In 491[illegible]	[illegible]	0.0[illegible] ±0.00[illegible]	0	< 0.01
In 491[illegible]	0.99	3.5 ±0.5[a]	0	0.19
In 491290	2.5	3.5 ±0.5[a]	1	0.16
In 491300	0.58	1.39 ±0.08[a]	3	0.07
In 491310	0.28	1.64 ±0.19[a]	0	0.03
In 491320	0.19	[illegible]	0	0.01
Sn 501330	[illegible]	[illegible]	0	< 0.01
Sn 501340	1.0[illegible]	[illegible]	1	0.11
Sn 501350	0.[illegible]	[illegible]	0	< 0.01
Sb 511340	[illegible]	[illegible]	0	[illegible]
Sb 511350	[illegible]	[illegible]	3	[illegible]
Sb 511360	[illegible]	[illegible]	0	[illegible]
Sb 511370	[illegible]	[illegible]	0	0.09
Te 511390	[illegible]	[illegible]	2	[illegible]
Te 511400	[illegible]	[illegible]	0	0.59
Te 511410	[illegible]	[illegible]	0	[illegible]
Te 511420	[illegible]	[illegible]	0	[illegible]
I 531370	[illegible]	[illegible]	3	[illegible]
I 531380	[illegible]	[illegible]	2	[illegible]
I 531390	2.[illegible]	[illegible]	1	[illegible]
I 531400	[illegible]	[illegible]	1	[illegible]
I 531410	0.[illegible]	39.[illegible]	0	[illegible]
I 531420	0.196	16.0	0	0.06
I 531430	0.328	18.0	0	< 0.01
Xe 541410	1.72	0.043±0.003	0	0.03
Xe 541420	1.24	0.41 ±0.03	0	0.14
Xe 541430	0.30	1.2	0	0.03
Xe 541440	1.00	0.73	0	< 0.01
Cs 551410	24.9	0.053±0.00[illegible]	1	0.13
Cs 551420	1.69	0.19 ±0.10	2	0.29
Cs 551430	1.76	1.[illegible] ±0.[illegible]	3	1.[illegible]
Cs 551440	1.001	2.6 ±0.[illegible]	2	0.56
Cs 551450	0.58	14.0 ±2.0	1	0.[illegible]
Cs 551460	0.335	13.[illegible] ±0.7	1	0.13
Cs 551470	0.21	25.0 ±3.0	1	< 0.01
Ba 561470	0.2	5.2 ±0.5[a]	0	0.01
Ba 561480	-	23.9 ±2.1[a]	0	0.14
Ba 561490	0.917	0.03	0	< 0.01
Ba 561500	1.796	0.14	0	< 0.01
La 571470	10.0	0.5 ±0.17[a]	0	0.06
La 571490	2.864	0.81	0	0.03
La 571500	0.648	0.94	0	< 0.01

[a] Measured subsequent to Ref. 1

[b] Change in Pn or uncertainty subsequent to Ref. 1

TABLE II

COMPARISON OF DELAYED NEUTRONS PER 100 FISSIONS

Fission Nuclide	Calculated ENDF/B-V	Evaluated ENDF/B-V	TITLE 1979[b]	Selected Measurements	Group Components of $\bar{\nu}_d$ (Calculated w. ENDF/B-V) 1	2	3	4	5	6
Th232F	4.76 ±0.34 (4.51)[a]	5.27	5.31 ±0.21	4.96±0.10[c]	3.6	17.5	16.6	15.6	21.7	4.9
Th232H	3.03 ±0.29 (2.77)	3.00	2.85 ±0.11	3.1 ±0.3[d]	1.8	14.5	16.3	41.1	16.6	7.4
U233T	0.846±0.066 (0.803)	0.74	0.667±0.029	0.66±0.04[e]	6.5	27.3	20.1	14.9	9.5	1.6
U233F	0.916±0.089 (0.870)	0.74	0.731±0.036	0.78±0.08[c]	7.4	27.5	21.1	10.7	11.3	1.3
U233H	0.708±0.045 (0.657)	0.47	0.422±0.025	0.43±0.04[d]	6.9	21.4	21.8	33.5	12.9	1.5
U235T	1.77 ±0.081 (1.66)	1.67	1.621±0.050	1.58±0.03[c]	2.9	22.1	15.9	35.4	19.0	4.6
U235F	1.98 ±0.18 (1.84)	1.67	1.673±0.036	1.71±0.12[c]	2.8	21.3	17.8	35.7	18.8	3.7
U235H	0.978±0.097 (0.902)	0.93	0.927±0.029	0.93±0.08[d]	4.5	22.2	20.2	35.6	15.2	2.3
U236F	2.26 ±0.19 (2.09)	-	2.21 ±0.24	-	2.3	20.3	15.4	36.1	21.7	4.
U238F	3.51 ±0.27 (3.13)	4.40	4.49 ±0.10	4.12±0.25[c]	1.1	15.7	11.0	36.0	28.9	7.2
U238H	2.69 ±0.21 (2.38)	2.60	2.73 ±0.08	2.83±0.13[d]	1.8	13.6	11.6	42.7	27.9	7.4
Np237F	1.28 ±0.13 (1.15)	-	-	-	3.0	23.8	14.3	35.9	20.2	2.7
Pu239T	0.769±0.058 (0.675)	0.645	0.628±0.018	0.61±0.05[c]	2.9	29.1	14.0	33.3	18.9	1.7
Pu239F	0.724±0.090 (0.612)	0.645	0.630±0.016	0.65±0.06[c]	3.4	26.1	14.4	37.9	20.5	2.2
Pu239H	0.387±0.062 (0.325)	0.430	0.417±0.016	0.43±0.04[d]	6.5	22.2	16.0	33.6	20.2	1.6
Pu240F	0.923±0.11 (0.798)	0.900	0.95 ±0.08	0.88±0.09[c]	2.8	26.7	12.5	34.3	20.7	3.1
Pu241T	1.58 ±0.13 (1.34)	1.62	1.52 ±0.11	1.57±0.15[c]	1.9	23.2	9.6	33.7	26.9	4.7
Pu241F	1.49 ±0.16 (1.24)	1.62	1.52 ±0.11	-	2.1	23.4	10.6	34.4	25.3	4.1
Pu242F	1.41 ±0.14 (1.20)	-	2.21 ±0.26	1.6 ±0.5[c]	2.6	24.7	10.1	34.0	23.7	4.9
Cf252S	0.690±0.092 (0.648)	0.09	-	-	4.6	30.1	9.1	30.3	24.2	1.6

[a] Values in parantheses used only measured Pn values.

[b] May 1979 revision of NSE 56 p.37, 1975 article to be published.

[c] Krick and Evans, NSE 47 p.311 (Here, average values between 0.1 and 1.8 MeV are listed).

[d] C. F. Masters et al. NSE 36 p.202 (High energy values at 14.9 MeV).

[e] G. R. Keepin et al. NSE 6 p.1 (Probable error converted to standard deviation).

There is now on effort to improve the calculated $\bar{\nu}_d$ using least squares data adjustment methods, incorporating integral data. To date, fission yield adjustments, limited to the most descrepant values in Table II, have resulted in significant improvements; the adjustment of Pn values is still in progress but appears less promising.

In Table I, a total of 30 precursors are identified as having neutron spectral measurements. For ^{235}U thermal fission these account for 82% of the total $\bar{\nu}_d$ and should, therefore, be adequate for calculations of the aggregate spectral shape.

References

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